Assessment of salinity hazard by Time Domain Reflectometry in flooded sandy paddy soils

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Abstract

Since the 1960's salinity has become an increasing constraint for rainfed rice production in the sandy lowlands of Northeast Thailand. In salt-affected areas, during flooded periods, very sharp gradients in salinity occurred inside the soil solutions from the soil surface to 20 cm depth. On the soil surface, water from precipitation and runoff maintain the salt contents at values that are not detrimental to the growth of rice. Inside the matrix of the soil, salt enrichment was found to be related to the ascent of the saline water from the aquifer. During the flooded period, survival of rice depends on the behaviour of a thin (less than 10 cm) fresh water lens. Previous field survey methods for assessment of salinity hazard have relied predominantly on soil conductivity measurements by electromagnetic induction. Although this method has been found useful in this context, its low vertical resolution prevented the detection of sharp salinity gradients at depth that is required to enhance the assessment of saline flooded sandy soils. The objective of the present study was to test the use of TDR measurements to describe the spatial distribution of the fresh water lens and mean conductivity of the top layer soil (0-20 cm) during the flooded period. A survey of water measurements with vertical uncoated waveguides was performed in a salinity contrasted flooded area leading to the measurement of average salinity of the surface soil layer (0-20 cm) and an estimation of the depth of fresh water lens. Surveys with TDR measurement of average salinity of the plough layer and determination of the salinity contrasts inside the first centimeters of the flooded sandy soil was demonstrated to be an effective method of the assessment of salinity hazard.

Introduction

Time Domain Reflectometry (TDR) has been widely used with the objective of measuring the water contents of soils and the method has been found particularly efficient and reliable in sandy soils. The method is based on the measurement of the time delay between an electrical impulse and its reflection at the end of waveguides implanted in the soil. This delay is related to the permittivity of the soil and then to the water content (Topp *et al.*, 1980). The effect of salinity has been shown to be a limitation of this method, because of its influence on the signal. However, under particular conditions the salinity effect will allow simultaneous measurement of conductivity and permittivity (Castaglione and Shouse, 2003). Several authors have focused on the responsiveness of TDR probes when the wave guide is implanted across a multilayered media (Nadler *et al.*, 1991; Feng and Lin, 1999; Todoroff and Sun Luk, 2001; Lin, 2003a and 2003b, Oswald *et al.*, 2003). In the case of a soil with contrasting water contents, the apparent permittivity could be computed by summing the propagation times (Topp *et al.*, 1982). This method is known as "refractive index mixing". Recently, Schapp *et al.* (2003) demonstrated that "refractive averaging was mostly prevalent when a small number of thick layers are oriented perpendicular to the probe" and arithmetic averaging was found to be more appropriate for multiple small layers systems.

Ploughed layers of sandy soils in flooded rice represented a particular media that is homogenous with respect to saturation in water and uniformity of texture. In salt-affected areas during flooded periods, very

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sharp gradients in salt contents occurred within the soil solution from the soil surface to 20 cm depth (Quantin *et al.*, 2005; Hammecker *et al.*, 2005). At the soil surface, water from precipitation and runoff maintained the salt content at values that are not detrimental to the growth of rice. However, inside the soil matrix, salt enrichment was found to be related to the ascent of the saline water from an aquifer. During the flooded period, survival of the rice crop was dependent on the behaviour of a thin (less than 10 cm) fresh water lens. Because of the low vertical resolution and the presence of the surface water, electromagnetic induction measurement appeared to be inappropriate to delimitate the fresh water lens. A destructive sampling performed using soil coring under water was likely to modify the fresh water lens behaviour. The objective of the present study was to evaluate the use of TDR measurements to describe the spatial distribution of fresh water lens and mean conductivity of the top layer soil (0-20 cm) during the flooded period in a sandy salt-affected paddy soil under cultivation.

Methods

All experiments were undertaken at the same site, near Khon Kaen in Northeast Thailand (N 16º 22′ 24.3′′E 102º38′43.3′′). The experimental field was selected in order to be representative of rainfed cultivated paddy fields common to the region that are affected by salinity.

Sodium and chloride make up approximately 98% of the soluble components of the soil solution (Saejew *et al.*, 2004).

Salt patches were defined as areas covered with salt crusts in dry season and low yields of rice during the flooded period. Two pairs of soil profiles where studied inside and outside two salt patches. The main characteristics of soil samples in the dry season and ranges of electrical conductivity measurements of soil solution when flooded are presented in Table 1. The ploughed layer was a sandy loam with no significant increase in clay content with depth. In the dry state, bulk density values increased with depth, but development of the high soil strength are not evident during the flooded period. Inside the saline patch, (profiles L25-S and L14-S), the conductivity of soil solution in dry season at 10cm were above 10dSm $^{-1}$ which is known to be detrimental to rice production (Zeng and Shannon, 2000), in contrast with outside the saline patch (L25-NS and L14-NS) were the conductivity of solutions were suitable for rice production.

TDR measurements were performed using a Trase field system connected to a 20 cm uncoated waveguide with three rods. The time window of the trace acquisition was generally settled to 40 ns which is the maximum value for this type of device. In order to establish conductivity calibration, TDR

Table 1. Selected characteristics of four soil profiles used in the study

Profile	Depth	Saturated paste conductivity [a]	Conductivity of solutions[b] (Flooded period 2003)		Texture[e]			Bulk Density[f]
		(Dry season 2003)	Average	standard error	Sand	Silt	Clay	
	cm	dS m^{-1}	dS m^{-1}		g.kg^{-1}			
L14-S	Surf.[c]	–	1.31	0.16	–	–	–	–
	0-10	54.1	**24.71**	2.05	591	356	52	1.72
	10-20	15.6	**19.65**	0.90	623	305	72	1.84
L14-NS	Surf.[c]	–	1.19	0.14	–	–	–	–
	0-10	6.4	3.49	0.43	598	353	49	1.69
	10-20	2.7	**8.14**	0.36	622	324	54	1.81
L25-S	Surf.[c]	–	1.09	0.14	–	–	–	–
	0-10	27.1	**16.04**	1.40	627	311	63	1.61
	10-20	19.7	**27.03**	0.82	700	246	54	1.75
L25-NS	Surf.[c]	–	1.01	0.14	–	–	–	–
	0-10	12.9	6.41	0.34	679	259	62	1.55
	10-20	6.5	**10.68**	0.73	703	241	56	1.81

[a]: Electrical conductivity of saturated paste in dry season, [b]: Conductivity of surface water and soil solutions from plastic cups at different soil depths (0.1 m and 0.25 m) in bold values indicates conductivity levels that are not suitable for rice production; [c]: Surface water [e]: Pipette method, f: 100 cm^3 cylinder method (average of 5 replications) in dry season 2003.

measurements were performed in a set of solutions with increasing conductivity (Ec_s) that were previously measured with a laboratory conductimeter. Calibration of the salinity measurements were based on the method given by Nadler, (1991) with an adaptation due to the larger ranges of values. Equations developed by Dalton *et al.* (1984) were found to be imprecise for the high and low conductivity values observed in the field. The impedance of the transmission line (R_L) was computed from the characteristic impedance of the cable (Z_0 = 50 Ω) and the total reflection coefficient (ρ_t).

$$R_L = -Z_0(1+\rho_t) / (\rho_t - 1) \quad [1]$$

where ρ_t was computed from the initial voltage value of the traces (V_0) and the last value of the response outside the influence of the reflections (V_f).

$$\rho_t = (V_0 - V_f) / V_0 \quad [2]$$

R_L is linked to the Ec_s of the solution by the geometric constant K_c defined as

$$K_c = Ec_{s*} R_L \quad [3]$$

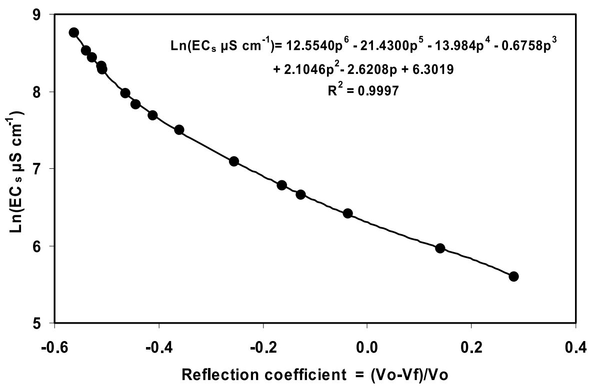

Figure 1. Measurements of the reflection coefficients of TDR traces with the waveguide immersed in solutions of in contrast to Nadler (1991), K_c was founded to be higher for low values of conductivity (Ec_s <1 dS m^{-1}) and lower for high values of Ec_s (Ec_s >3 dS m^{-1}). Between 1 and 3 dS m^{-1}, K_c was found comparable with the values indicated by the authors [K_c = 30-45]

This difficulty was overcome by adjusting a polynomial expression between the logarithm of Ec_s and the total reflection coefficients observed (Figure 1).

$$\mathrm{Ln}(Ec_s) = 12.55\rho_t^6 - 21.43\rho_t^5 - 13.98\rho_t^4 - 0.68\rho_t^3 + 2.10\rho_t^2 - 2.62\rho_t + 6.30 \quad [4]$$

with Ec_s in µS cm^{-1} known electrical conductivity. Fitted polynomial expression used as calibration curve in this study (Eq. 4).

For survey purposes, measurements where spaced 2.5m apart. The waveguide, 0.2m long, was entirely driven into the soil between rice plants, in a vertical position under the water of the rice field. The conductivity for the entire length of the probe was converted introducing the reflection coefficient in equation 4. In the profiles described in Table 1, instead of a simple measurement of the entire depth of the probe, 5 measurements were performed at the same point. Firstly, measurement was performed inside the surface water, the waveguide was then driven vertically into the soil, with measurement record at depths 0.05, 0.1, 0.15, 0.2 m. Last measurement was then performed over the entire length of the probe inside the soil. When the depth of the surface water was less than 0.15m the first measurement at 0.05m was not possible. The reflection coefficients (ρ_{twater} ρ_{t5cm}, ρ_{t10cm}, ρ_{t15cm}, ρ_{t20cm}) were calculated from the traces and computed into conductivity values using the equation 4 (Ec_{sw}, Ec_{5cm}, Ec_{10cm}, Ec_{15cm}, Ec_{20cm}). A four layer approach was applied to compute the conductivity layer by layer assuming additive behaviour of conductivity parameter.

$$Ec_{[0\text{-}5cm]} = [0.20Ec_{5cm} - 0.15Ec_w] / 0.05 \quad [5]$$

$$Ec_{[5\text{-}10cm]} = [0.20Ec_{10cm} - 0.10Ec_w - 0.05Ec_{[0\text{-}5cm]}] / 0.05 \quad [6]$$

$$Ec_{[10\text{-}15cm]} = [0.20Ec_{15cm} - 0.05Ec_{[5\text{-}10cm]} - 0.05Ec_{[0\text{-}5cm]} - 0.05Ec_w] / 0.05 \quad [7]$$

$$Ec_{[15\text{-}20cm]} = [0.20Ec_{20cm} - 0.05Ec_{10\text{-}15cm} - 0.05Ec_{[5\text{-}10cm]} - 0.05Ec_{[0\text{-}5cm]}] / 0.05 \quad [8]$$

Results

TDR measurements of two soil layers are presented in Figure 2. Traces presented typical shapes for the depths of implantation 0.1, 0.15, 0.20 m. The transition from the cable to the rods caused a decrease of voltage. This decrease was associated with the thickness of the water layer. Sharp increases in voltage were observed because of the transition from a liquid to a saturated porous media. A time shift corresponding to the time necessary for the pulse to reach and return from contact with the water layer and the surface of the soil. Relative increases of voltage ranged from 3.8 to 12.8%. If only 0.05m of the waveguide were inserted in the soil, the influence of the transition between water and saturated soil was combined to the reflection that took place at the end of the probes and only a small effect on voltage was perceptible allthought a clear shift in time (almost 1 ns) was observed due to the

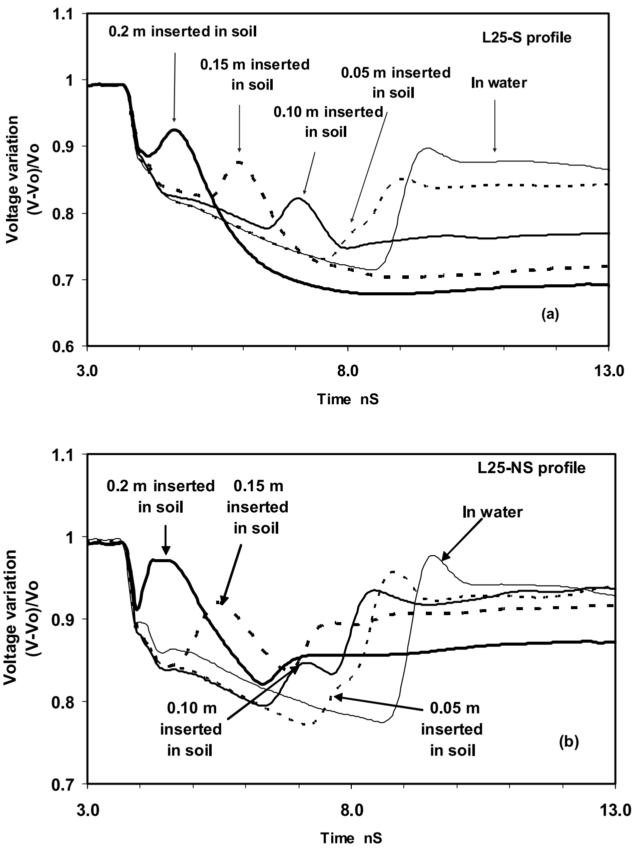

Figure 2. Traces of TDR measurements in L25-S (a) and L25-NS (b) profiles for different positions of the probe relative to the surface of the soil (totally inserted, 0.05, 0.1, 0.15 m out of the soil, inside the field water). Arrows are pointing to the effect of a resistive layer representative of the transition between water and soil

permitivity effect. In the 4 profiles, the speed of reflection impulse values were between 3.9 10^7 ms $^{-1}$ and 4.010 ^{7} m s^{-1}. The application of the equation of Topp *et al.* (1980) indicated volumetric water contents of 0.64 and 0.57 cm^3cm^{-3} in the 0-0.2 m layer.

Conductivity estimates using equations from 1 to 8 are presented in Figure 3. Near the surface conductivity values of the soil were found to be in a narrow range [0.5-0.8 dS m^{-1}]. Profiles L14-NS and L25-NS showed slight increases in conductivity with depth in the ploughed layer reaching 1 dS m^{-1}. On the contrary, both profiles located in the saline patch (L25S and L14S) showed a strong increase in conductivity with depth since the conductivity of the 0.05-0.1 m layer reached values higher than 1.7 dS m^{-1}.

Conductivity map of the first layer was constructed using equations 1, 2, 3 and 4 and values were interpolated and are presented in Figure 4. The result was compared to a classical salinity survey map using the same locations but developed 3 months latter.

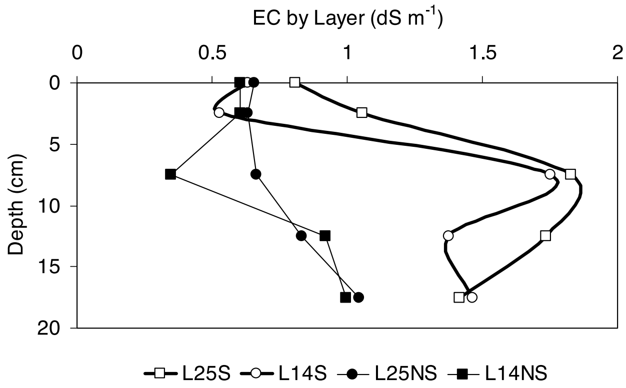

Figure 3. Estimation of the conductivity values by layer for four profiles

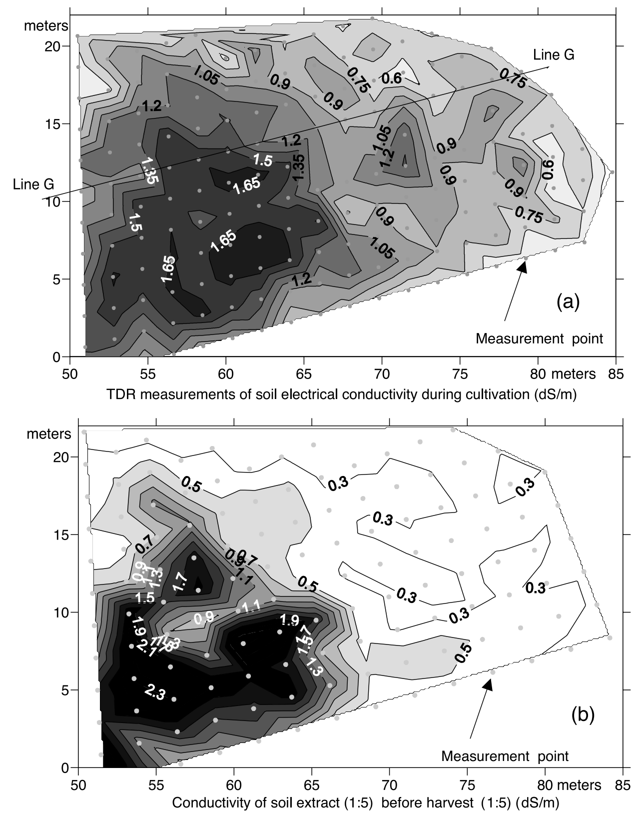

Figure 4. Survey of soil electrical conductivity measured by TDR (dS m^{-1}) (a) compared to conductivity of 1:5 soil extracts (dSm $^{-1}$) (b) using triangulation with linear interpolation. Line G traces

It is to note that the two maps are comparable in that they both highlight the presence of the saline patch.

The shape of the traces are likely to provide suplementary information of the existence of a relatively resistant layer at the soil surface. For example, points along the line G, presented in Figure 4, had their corresponding traces depicted in Figure 5.

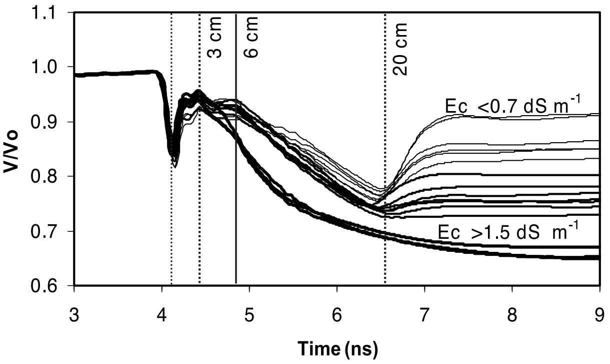

Figure 5. TDR traces along the line G, as indicated in Figure 4. (3 cm, 6 cm and 20 cm are indicating the distances along the waveguides assuming a constant permittivity, illustrating the main changes in reflection coefficient)

Two groups of traces were clairly identified.

a) Traces of soil profiles with conductivity values higher than 1.5 dS m^{-1} could be used to determine the water content. The sharp voltage peak of short duration indicated the thiness of the resistive layer at the surface, which was found to have a thickness less than 0.03 m.

b) Traces of soil profiles with conductivities between 0.7 and 1.5 dS m^{-1} could be used to determine soil water contents. A wider peak in voltage at the beginning of the curve indicated that, after the transition from water to soil, the conductivity stayed low in the first layer with a thickness that could be greater than 6 cm.

Conclusions

Estimation of bulk conductivity by TDR of the upper surface layer of a saline sandy soil could be performed during the flooding period. The method was quicker than 1:5 soil and water extracts and was far less destructive. Unlike determination of conductivity by electromagnetism induction, the measurements achieved using TDR traces were representative only of the ploughed layer.

Inside the saline patches, the water content measurement could not be performed because of the lack of reflection at the end of the waveguides. The four profiles studied by measurements at incremental depths indicated that inside the saline patch the fresh water lens thickness was less than 0.05m. The shape of the TDR traces suggested that similar circumstances existed inside the saline patch. In contrast outside the saline patch, the low conductivity layer was thicker and the trace had distinctive characteristics. The shape of the traces could be used to identify the distribution of salinity over a given depth.

Surveys with TDR measurement of average salinity of the ploughed layer and qualitative determinations of salinity inside the few first centimeters of the flooded sandy soil has been demonstrated to be an effective method for the assessment of salinity hazard. Further developpement will require a simulation model to test the sensibility of the relation between the traces and the evolution of salinity with depth.

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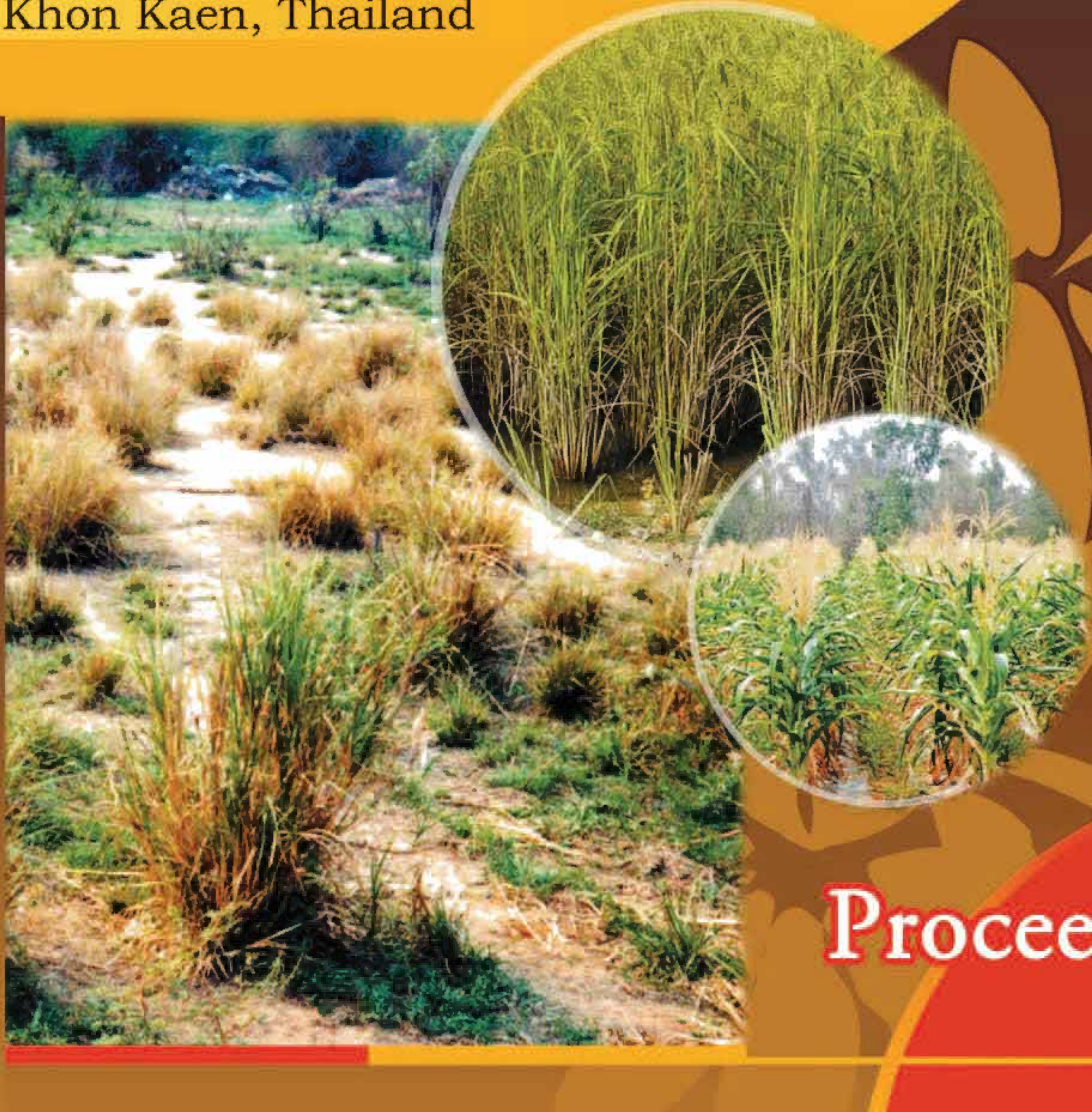

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